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Selection of the critical plane orientation in two-parameter multiaxial fatigue failure criterion under combined bending and torsion

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Abstract

The present paper is focused on engineering application of the algorithm of fatigue life calculation under multiaxial fatigue loading. For that reason, simple two-parameter multiaxial fatigue failure criterion is proposed. The criterion is based on the normal and shear stresses on the critical plane. Experimental results obtained under multiaxial proportional, non-proportional cyclic loading and variable-amplitude bending and torsion were used to verify the proposed two-parameter criterion and other well-known multiaxial fatigue criteria. Elastic–plastic behaviour of the bulk material was taken into account in calculation of the stress/strain distribution across the specimen cross-section. It is shown that the proposed two-parameter multiaxial fatigue failure criterion gives the best correlation between the experimental and calculated fatigue lives.

Keywords: Critical plane approach; Fracture plane orientations; Multiaxial loading; Local approach; Variable-amplitude loading; Fatigue damage accumulation

1. Introduction

Various multiaxial fatigue failure criteria based on the critical plane approach have been proposed [1–11]. This concept, which is related to the crack initiation phenomenon, was firstly proposed by Stanfield [9] in 1935, and has been developed since then by Stulen and Cummings [10], Findley [2] and others [1]. It assumes that the fatigue failure of the material is due to some stress or/and strain components acting on the critical plane. It is based upon the experimental observation that in metallic materials fatigue cracks initiate and grow on certain planes. Although, the critical plane approach concerns the crack initiation process that is usually related to fatigue failure at high cycle fatigue regime [11], it was successfully used also at low cycle fatigue regime [3].

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Nomenclature

b	fatigue strength exponent for fully reversed push–pull loading
c	fatigue ductility exponent for fully reversed push–pull loading
D	damage degree
E	Young's modulus
F	generalised fatigue damage parameter
G	Kirchhoff's modulus
k	material coefficient of normal stress influence
K	array of material coefficients ($K = \{b, c, Q, \text{etc.}\}$)
M_b	bending moment
M_t	torsional moment
N_{cal}	calculated number of cycles to failure
N_f	number of cycles to failure in the S–N curve
N_τ	number of cycles corresponding to the fatigue limit τ_{af}
m_σ	exponent of the S–N curve for fully reversed ($R = -1$) push–pull loading
m_τ	exponent of the S–N curve for fully reversed ($R = -1$) torsion loading
p	Serensen–Kogayev coefficient
q	material parameter for a given fatigue life N_f
Q	fatigue limit
t	time
α	angle between unit-normal vector $\vec{n}$ to the considered plane orientation and the specimen axis z
δ	phase shift between the bending and torsion moments
ε'_f	fatigue ductility coefficient for fully reversed push–pull loading
$\gamma_{ns,a}$	shear strain amplitude
λ_M	ratio of the maximum moments ($M_{t,max}/M_{b,max}$)
$\lambda_{\tau\sigma}$	ratio of the maximum stresses ($\tau_{zx,max}/\sigma_{zz,max}$)
v	Poisson's ratio
σ_{af}	fatigue limit for fully reversed ($R = -1$) push–pull loading
σ_n	normal stress component on the plane with unit-normal vector $\vec{n}$
σ_y	yield stress
σ_u	ultimate tensile strength
σ_{zz}	normal stress component on the plane normal to specimez axis $\mathbf{z}$
σ_1	maximum principal stress
τ_{af}	fatigue limit for fully reversed ($R = -1$) torsion loadig
τ_{ns}	shear stress component on the plane orientated by the unit-normal vector $\vec{n}$
$\tau_{ns,a}$, $\sigma_{n,a}$	shear and normal stress amplitudes, respectively
τ_{zx}	shear stress component in direction $\mathbf{x}$ on the plane normal to specimen axis $\mathbf{z}$

Subscripts and others

a	amplitude
af	fatigue limit
eq	equivalent
max	maximum
n	in the plane with normal vector $\vec{n}$
ns	along direction $\vec{s}$ on the plane with normal vector $\vec{n}$

Depending on the scale of observation and test conditions (loading level, temperature, material type, state of stress, etc.) material exhibits different crack behaviour and different models of crack types were proposed. The shear cracks are formed on the maximum shear stress plane and Forsyth [13] called this process as Stage I.